LETTER

NCT-WES: A new single moderator directional neutron spectrometer for neutron capture therapy. Experimental validation

To cite this article: R. Bedogni *et al* 2021 *EPL* **134** 42001

A Letters Journal Exploring the Frontiers of Physics

May 2021

EPL, **134** (2021) 42001
doi: 10.1209/0295-5075/134/42001

www.epljournal.org

NCT-WES: A new single moderator directional neutron spectrometer for neutron capture therapy. Experimental validation

R. Bedogni[1(a)], A. Lega[1,2], A. Calamida[1], V. Monti[2,3], A. I. Castro-Campoy[4], L. Menzio[2,3], T. Napolitano[1], A. Pola[5], D. Bortot[5], A. Pietropaolo[6], M. Costa[2,3] and S. Altieri[7,8]

[1] *INFN, Laboratori Nazionali di Frascati - via Enrico Fermi 40, 00044, Frascati, Italy*
[2] *Università degli Studi di Torino - via P. Giuria 1, 10125, Torino, Italy*
[3] *INFN, Sezione di Torino - via P. Giuria 1, 10125, Torino, Italy*
[4] *Departamento de Investigación en Polímeros y Materiales, División de Ingeniería, Universidad de Sonora Hermosillo, Mexico*
[5] *Politecnico di Milano, Dipartimento di Energia - via La Masa 34, 20156 Milano. Italy*
[6] *ENEA C.R. Frascati, Department of Fusion and Nuclear Safety and Security - via Enrico Fermi 45, 00044, Frascati (Roma), Italy*
[7] *Università degli Studi di Pavia - via Bassi, 6, 27100 Pavia, Italy*
[8] *INFN, Sezione di Pavia - via Bassi, 6, 27100 Pavia, Italy*

received 18 December 2020; accepted in final form 3 May 2021
published online 27 July 2021

Abstract – A directional neutron spectrometer called NCT-WES (Neutron Capture Therapy Wide Energy Spectrometer), conceived as a spectrometric beam monitor in neutron capture therapy, was designed and prototyped. As other types of single moderator neutron spectrometers, NCT-WES condenses the functionality of Bonner Spheres in a single moderator embedding multiple thermal neutron detectors in previously optimized positions. NCT-WES is a polyethylene cylinder with 36 cm diameter and 41.5 cm height. To achieve a sharply directional response, the sensitive part is shielded with a thick barrier made of polyethylene and borated rubber, except in the direction identified by the collimating aperture. The size, geometry, materials and detector locations were previously optimized to emphasise the spectrometric capability in the epithermal range. TNPD-type thermal neutron detectors, consisting of $1\,\mathrm{cm}^2$ silicon p-i-n diodes covered with ^{6}LiF are used as internal thermal neutron detectors. The simulation model of NCT-WES was experimentally verified by exposing the prototype in the reference neutron field of ^{241}Am-Be available at the Politecnico di Milano. The count rate in the NCT-WES internal detectors, as calculated from the simulation model, coincided with the experimental ones within about $\pm 2\%$, confirming the high degree of accuracy of the NCT-WES simulation model. Aspects related to the future use of NCT-WES in therapeutic neutron beams are finally discussed.

Introduction. – Boron Neutron Capture Therapy (BNCT) is experiencing renewed interest, due to the availability of accelerator-based therapy units that can be built in hospitals and, with respect to reactor-based facilities, potentially extend the access to this therapy to a much larger population [1]. Correspondingly, researches are being promoted in the related physical, pharmaceutical and clinical fields. A recent IAEA Technical Meeting [2] summarized the advances in these fields. As far as the physical dosimetry of BNCT is concerned, several methods have been used [3] such as gold foils, ion chambers, thermo-luminescent dosemeters, and microdosimeters. In addition, it is today common experts' opinion that the neutron spectrum at the beam port should be measured [2]. Existing neutron spectrometers have been proposed [4] for this task, but at present they do not cover the whole energy range of interest, typically spanning from thermal up to MeV energies. This work describes a new directional spectrometer, especially conceived for use in neutron captures therapy, called NCT-WES (Neutron

(a) E-mail: roberto.bedogni@lnf.infn.it (corresponding author)

Capture Therapy Wide Energy Spectrometer) and developed within the INFN project ENTER_BNCT.

NCT-WES belongs to the family of the single moderator neutron spectrometers [5–9]. Such devices were conceived to condense the functionality of Bonner Spheres in a single moderator with specific geometry, embedding multiple thermal neutron detectors in previously optimized positions. They are similar to Bonner Spheres in terms of energy interval, operation and accuracy, but they require only one exposure to determine the whole neutron spectrum. As the internal thermal neutron detectors are simultaneously recorded, these devices are suited to operate as real-time spectrometers. The spectrum is obtained by processing them, together with the response matrix and the uncertainties, with a traditional few-channel unfolding code.

NCT-WES has the appearance of a polyethylene cylinder with 36 cm diameter and 41.5 cm height. Six thermal neutron detectors are located at different depths along the axis. A collimating aperture selects only neutrons from the desired direction. As shown elsewhere [10] the size, geometry, materials and detector locations were optimized to emphasise the spectrometric capability in the epithermal range, which is of interest for the neutron capture therapy.

This work describes the first NCT-WES prototype, entirely built at INFN-LNF for both the mechanical parts and the internal thermal neutron detectors. The latter are TNPD-type thermal neutron detectors [6], consisting of silicon p-i-n diodes with 1 cm^2 active area, covered with ^{6}LiF. A very detailed simulation model of the spectrometer was developed using MCNP 6 [11]. This model was experimentally validated by exposing the prototype in the reference neutron field of ^{241}Am-Be available at the Politecnico di Milano [12]. The count rate in the NCT-WES internal detectors, as calculated from the simulation model, coincided with the experimental ones within about ±2%, confirming the high degree of accuracy of the NCT-WES simulation model.

NCT-WES design. – According to the final design described elsewhere [10] and sketched in fig. 1, NCT-WES appears as a HDPE (High-Density Polyethylene) cylinder with diameter 36 cm and total length 41.5 cm. The dimensions of the cylinder as well as the location of detectors have been chosen to maximize the "spectrometric capability" of the device in the epithermal domain, *i.e.*, the degree of differentiation between the response functions associated to different detector positions. The HDPE collimator (label A in fig. 1) is 19.5 cm in length and its collimating aperture (label B), 12 cm in diameter, is internally lined with 0.5 cm of borated plastic SWX-238 from Shieldwerx (label C). Six thermal neutron detectors (D), located along the cylindrical axis, are contained in the HDPE capsule (label E, 20 cm in diameter, 13.5 cm in length). In order to facilitate maintenance, they are embedded in an extractable HDPE drawer (labels F and H). An external shield made of 0.5 cm of SWX-238 (label C) plus 7.5 cm

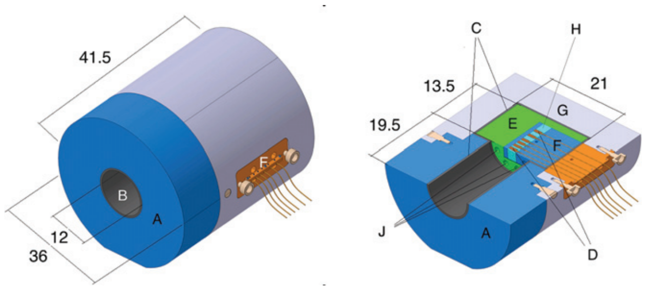

Fig. 1: Schematics of the NCT-WES spectrometer. All parts are in HDPE, excepted the lining of the collimating aperture, made of borated rubber. Values are in cm.

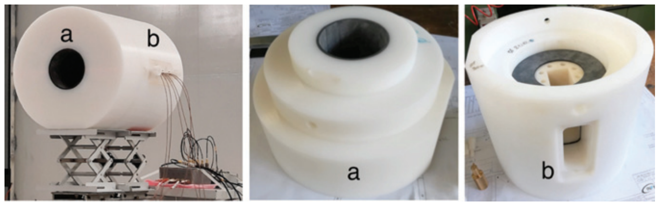

Fig. 2: NCT-WES. On the left, the assembled prototype with the detector drawer inserted. At the centre, the part a including the collimator. On the right, the part b including the sensitive capsule and its lateral protection. Air penetrations are visible. The drawer is extracted.

of HDPE (label G) protects the capsule against neutrons arising from undesired directions. The centre of the shallowest detector is located at 0.72 cm depth from the end of the collimator. Detectors spacing (centre to centre) is 1.3 cm from the 1st to the 4th, and 2 cm from the 4th to the 6th. The detectors are parallelepipeds with external dimensions 0.32 cm × 1.5 cm × 1.3 cm and are connected through a 2 mm diameter coaxial cable. Their response is discussed in the next section. It should be noted that NCT-WES can be adapted to allocate internal detectors with different size by simply replacing the polyethylene piece labelled H. Label J refers to eight cylindrical air cavities, 1.3 cm in diameter, designed to enhance the response of deeper detectors relying on neutron streaming. The centres of these cavities are equally spaced on a circumference with radius 4.25 cm centred on the NCT-WES cylindrical axis. The assembled NCT-WES is shown in fig. 2. Part a includes the collimator and part b the sensitive capsule and its lateral protection.

NCT-WES internal thermal neutron detectors. – The thermal neutron detectors developed for NCT-WES are called TNPD (Thermal Neutron Pulse Detector). These are 1 cm^2 windowless p-i-n diodes made sensitive to thermal neutrons through deposition of about 30 μm of ^{6}LiF on the sensitive face. TNPDs are connected to a customised nuclear spectroscopy chain formed by a CREMAT CR110 charge preamplifier, a CR200 shaper amplifier (shaping time 2 μs) and a digitizer. As explained in ref. [6], the genuine neutron-induced events are separated

from those induced by photons by comparing the pulse height with a threshold, fixed to 0.6 V.

TNPD internal structure was simulated with MCNP 6. The detector reading, intended as the number of pulses from alpha or tritium particles escaping the ^{6}LiF radiator and reaching the silicon active layer, was assumed to be proportional to the number of (n, t) capture reactions in the ^{6}LiF radiator. The scaling factor F, indicating the number of measurable pulses per (n, t) capture reaction in the ^{6}LiF radiator, was derived in an experiment at HOTNES (Homogeneous Thermal Neutron Source of ENEA/INFN) [13] applying the following procedure:

– The TNPDs were exposed in the HOTNES reference irradiation position (+50 cm from the facility bottom), obtaining the experimental count rate R. Considering all six TNPDs, an average R value of 23.76 s^{-1} was obtained, with ±1.5% detector-to-detector variability (one s.d.).

– An MCNP 6 simulation was run, including the whole HOTNES structure with the TNPD in the irradiation position. By multiplying the simulated number of (n, t) capture reactions in the ^{6}LiF radiator per source neutron $(2.850 \pm 0.001) \times 10^{-5}$ and the emission rate of the HOTNES Am-B source, $(3.50\text{E} \pm 0.07) \times 10^6$ s^{-1}, the expected rate of (n, t) capture reactions is $\rho = (99.8 \pm 2.0)\ s^{-1}$.

– The scaling factor was derived as $F = R/\rho = (0.238 \pm 0.006)$. If the ^{6}LiF radiator was infinitely thin and all charged particles impinging the silicon were detected, F would be unitary. However, the radiator is as thick as the range of the tritons, thus a significant fraction of charged particles reaches the diode sensitive volume with degraded energy. Those who produce pulses below the 0.6 V threshold are not counted, causing the F value to be significantly lower than one.

NCT-WES response matrix. – The response matrix of the NCT-WES (units: cm^2), shown in fig. 3, is the result of an extensive Monte Carlo simulation campaign.

The code MCNP 6 [11] was used with the neutron cross-section libraries ENDF/B-VIII [14] below 20 MeV and room temperature cross-section tables in polyethylene, $S(\alpha, \beta)$. The spectrometer was modelled according to the scheme in fig. 1. The response matrix was obtained by simulating an irradiation with a uniform parallel neutron beam having diameter 36 cm (the same diameter of the NCT-WES cylinder), and directed towards the collimator entrance. The response is the number of (n, t) events in the TNPD ^{6}LiF radiator, per unit incident neutron fluence, multiplied by the scaling factor F, as a function of the detector position and the neutron energy.

The labels "Pos 1" to "Pos 6" in fig. 3 indicate the detector positions, from the shallowest to the deepest.

The maximum in the response functions shifts from fractions of eV (Pos 1) to about 1–2 MeV (Pos 5 and Pos 6).

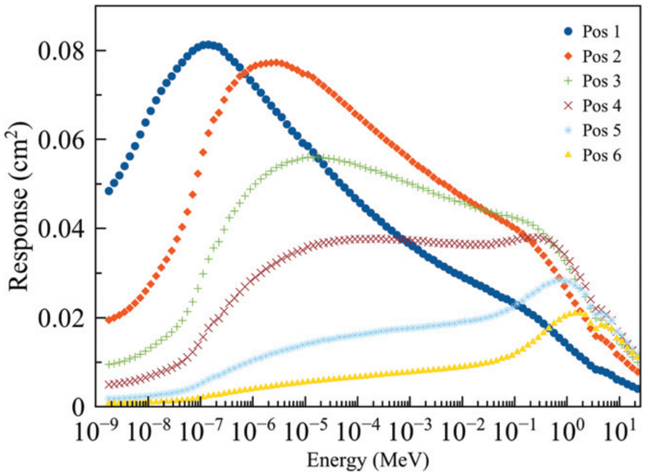

Fig. 3: NCT-WES response matrix. The response is the expected number of measurable pulses in the TNPD, per unit incident fluence, as a function of the energy and the detector position.

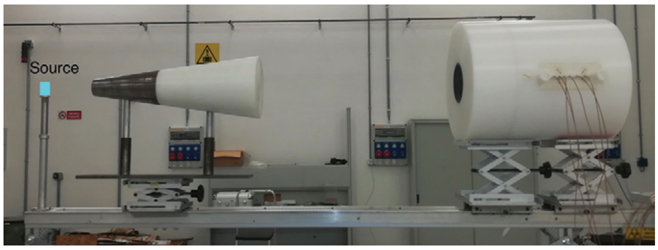

Fig. 4: NCT-WES exposed in front of the ^{241}Am-Be source with the shadow cone interposed.

As demonstrated in ref. [10], the degree of differentiation of these curves guarantees a good resolving power in the epithermal domain, which is of interest for the neutron capture therapy.

Validation of the Monte Carlo model. – The NCT-WES simulation model was verified using the reference neutron field from a lightly encapsulated ^{241}Am-Be source available at the Politecnico di Milano. As shown in fig. 4, the source is positioned in a panoramic irradiation bench. The low-scattering room has size 12 m × 12 m × 6 m. The source-detector line lies at 2 m from the floor. Neutrons emitted in the direction normal to the cylindrical axis of the ^{241}Am-Be source are used for irradiation. The source-specific neutron spectrum and the un-collided fluence rate at 1 meter from the source were measured with Bonner Spheres in a previous work [12].

The following procedure was adopted to validate the NCT-WES simulation model:

1) The spectrometer was positioned with its front face at 1.25 m from the source. For estimating the contribution of the room-scattered neutrons in the NCT-WES internal detectors, a shadow cone [15] with small diameter 4.95 cm and large diameter 19 cm was used.

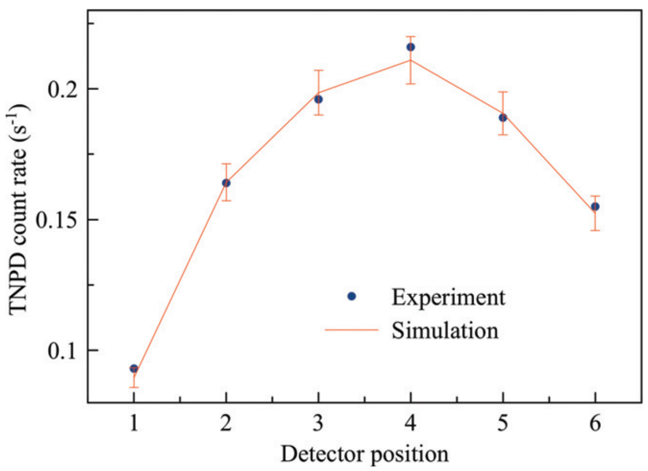

Fig. 5: Experimental and simulated count rates in the NCT-WES internal detectors exposed to the un-collided field (total field-shadow cone) from the ^{241}Am-Be radiation. Only the uncertainties on the simulated profile (<5%) are reported. The line is only a guide for the eye.

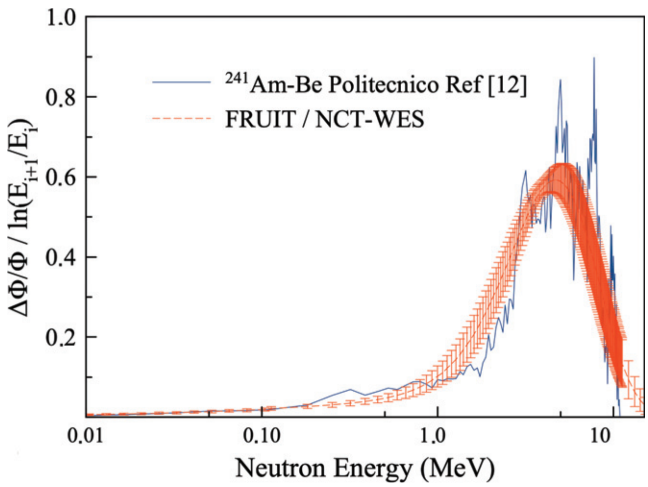

Fig. 6: Unfolded spectrum, derived by applying the FRUIT code to the NCT-WES data with, compared with the literature spectrum of the ^{241}Am-Be source of the Politecnico di Milano.

Acquisition time for the shadow cone measurements was in the order of 20000 seconds, achieving statistical uncertainties of about 7–8% on the number of counts in TNPDs above the 0.6 V threshold. The total field measurement lasted about 60000 seconds, with statistical uncertainties of about 1%. For each detector position, the observed count rate due to the un-collided component was evaluated by subtracting the count rate obtained with the shadow cone from the total count rate. When plotting this quantity against the detector position, the profile "Experiment" in fig. 5 is obtained. Uncertainties on this profile are lower than ±2%.

2) The experimental set-up described in point 1) was accurately simulated with MCNP in both "shadow cone" and "total field" configurations. The neutron spectrum attributed to the ^{241}Am-Be was the one specifically measured for that source [12]. The source was modelled as a uniform "volume" source in vacuum, occupying the actual volume of the capsule. The "simulation" count rate Q_{sim} was derived, for a given detector and cone/total field configuration, as follows:

$$Q_{\mathrm{sim}} = N_{\mathrm{n,t}} \times F \times B,$$

where $N_{\mathrm{n,t}}$ is the simulated number of (n, t) capture reactions in the ^{6}LiF radiator of the TNPD per source neutron; F is the scaling factor, previously derived; B is the emission rate of the ^{241}Am-Be source, $(2.12 \pm 0.08) \times 10^{6}\ \mathrm{s}^{-1}$.

For each detector position, the simulated count rate due to the un-collided component was evaluated by subtracting the simulated count rate with the shadow cone from that obtained in total field condition. When plotting this quantity against the detector position, the profile "Simulation" in fig. 5 is obtained. Uncertainties on this profile are lower than ±5%. The experiment/simulation ratio, averaged over the six detector positions, is 1.01 (variability ±2%, 1 s.d.), confirming the very high degree of accuracy of the model used to simulate the spectrometer and the measurement set-up.

Unfolding test. – To complete the validation of the spectrometer, an unfolding test was performed based on the ^{241}Am-Be measured data. The FRUIT code [16] was selected for the test.

The unfolding is known to be an underdetermined process, as it pretends to determine a multi-group neutron spectrum starting from usually less than ten measurements (the detector count rates). Thus a given amount of pre-information, in addition to the response matrix and the count rates, is always needed to orientate the iterative process towards a physically meaningful solution. The classical way to provide pre-information is using a realistic spectrum, usually determined via simulation, to start the unfolding process (guess spectrum). Fine structures such as narrow peaks will not appear in the solution if they have not been introduced in the guess spectrum.

Another approach, available in FRUIT, is that based on parameterised spectra. No guess spectrum is required to the user. As described in [16], the code models the neutron spectrum as the superposition of elementary continuous spectra. Compared to the spectra obtained by guess-based approaches, the parametric spectra appear less defined as they do not include fine structures. However, being less dependent on the pre-information, the parametric approach is more suited to reveal the real spectrometric capability of a spectrometer.

For this reason the parametric approach was used for the current test, obtaining the results in fig. 6. The lethargy plots of fig. 6 report the the quantity $\Delta\Phi_i/\Phi/\ln(E_{i+1}/E_i)$,

where $\Delta\Phi_i$ is the fluence in the i-th energy interval, Φ the total fluence, E_i is the lower limit of the i-th energy interval.

The unfolded NCT-WES spectrum has uncertainties specified bin by bin. FRUIT derives these uncertainties by propagating uncertainties on the input quantities (response matrix and sphere counts) through the unfolding process [17]. The shape of the unfolded spectrum is satisfactory, and the ratio unfolded/delivered fluence is 0.988.

Discussion. – As shown in the previous sections, the experiment fully confirms the simulation model of the spectrometer. The fact that experiment and simulation perfectly fit, without needing any scaling factor, particularly confirms that NCT-WES internal detectors are well known.

The unfolding test, conducted without the support of a detailed guess spectrum, confirms that the spectrometer has adequate spectrometric capability to correctly reproduce the ^{241}Am-Be spectrum.

In view of the future use of NCT-WES in neutron capture facilities, the following points also need some discussion:

– Rejection of scattered component. The contribution of the room- and air-scattered radiation to the readings of the NCT-WES internal detectors should be in principle as low as possible, as the instrument should only measure the contribution from the beam port and neglect room scattering. The measured quotient between cone reading and total field reading was in the order of 6–7% for the experiment described in this work. But it should be kept in mind that the average energy of the ^{241}Am-Be spectrum (4.16 MeV) is considerably larger than those of typical BNCT spectra, expected to be in the keV region. At these lower energies NCT-WES is much more efficient in suppressing neutrons from unwanted directions [10].

– Type of internal detectors and field intensity. As one of the first objectives of the ENTER_BNCT project was validating the structure and the geometry of NCT-WES, the first prototype was equipped with highly sensitive TNPD type detectors. With these detectors, the validation task could be easily performed in small-scale reference neutron facilities like the one at the Politecnico di Milano. On the contrary, the neutron fluence rate expected in neutron capture therapy beams is likely to be in the order of $10^9\,\mathrm{cm^{-2}\,s^{-1}}$ [18], which is orders of magnitude higher than the one used in this work. TNPDs suffer from thermal neutron damage at accumulated fluence rates in the order of $10^{11}\,\mathrm{cm^{-2}}$ [6], so they will not be suited for therapy level facilities. Consequently, before using NCT-WES in therapy beams, internal TNPDs will be replaced by mm^2-scale radiation-resistant silicon carbide thermal neutron detectors [19], whose use is well established within the group. With these smaller detectors, expected acquisition times in therapy-grade beams are in the order of minutes.

  Prior to their use in NCT-WES, these new detectors will be fully modelled and experimentally characterised. A new response matrix will be derived, but the new simulation model will only slightly differ from the one used in this work, and its accuracy is expected to be very high as it is in this work. From the mechanical point of view, the detector replacement will be easy, as only a small polyethylene piece (label H in fig. 1) will be replaced to allocate the new detectors.

– Comparison with existing single moderator neutron spectrometers. Another cylindrical single moderator spectrometer, called CYSP [5–9], was developed in the past to cover the energy range from thermal up to GeV neutrons. Compared to CYSP, NCT-WES is much more compact and light (40 kg against 120 kg) as the energy range of interest is considerably reduced. In addition, to emphasise resolving power in the epithermal domain, the position and spacing of internal detectors have been totally reassessed and modified.

Conclusion. – NCT-WES is a spectrometric beam monitor intended for beam characterisation and quality assurance in neutron capture therapy. Its first prototype, designed through extensive Monte Carlo simulations, was successfully tested in a reference neutron field of Am-Be. For these purposes, it was equipped with highly sensitive TNPD detectors. The next step, in view of its use in highly intense therapy beams, will be replacing the radiation-damage–prone TNPD detectors by mm^2-scale radiation-resistant silicon carbide thermal neutron detectors, whose use is well established within the group. It is expected, as a result of the ENTER_BNCT project, that NCT-WES will constitute a compact, radiation-tolerant, and easy-to-use instrument for BNCT clinical practice.

* * *

This work has been supported by project ENTER_BNCT from INFN (Commissione Scientifica Nazionale 5). The staff of the INFN-LNF SPCM (Servizio Progettazione e Costruzioni Meccaniche), especially Mr. Alberto De Paolis, is greatly acknowledged.

REFERENCES

[1] Barth R. F. and Grecula C., *Appl. Radiat. Isot.*, **160** (2020) 109029.

[2] IAEA, *Report of the IAEA Virtual Technical Meeting on "Advances in Boron Neutron Capture Therapy". IAEA Headquarters, Vienna, Austria, 27–31 July 2020* (draft).

[3] Daquino G. G. and Voorbraak W. P., *A Review of the Recommendations for the Physical Dosimetry of Boron*

Neutron Capture Therapy (BNCT) (EUR, Luxembourg), 2008.
[4] Santos D., Sauzet N., Guillaudin O. and Muraz J.-F., *EPJ Web of Conferences*, **231** (2020) 05003.
[5] Bedogni R., Gómez-Ros J. M., Pola A., Bortot, D., Gentile A., Introini M. V., Buonomo B., Lorenzoli M., Mazzitelli G. and Sacco D., *Nucl. Instrum. Methods A*, **782** (2015) 35.
[6] Bedogni R., Bortot D., Pola A., Introini M. V., Lorenzoli M., Gomez-Ros J. M., Sacco D., Gentile A., Buonomo B., Palomba M. and Grossi A., *Nucl. Instrum. Methods A*, **780** (2015) 51.
[7] Bedogni R., Gómez-Ros J. M., Alikaniotis K., Pagano G., Pillon M. and Pietropaolo A., *Nucl. Instrum. Methods A*, **927** (2019) 151.
[8] Bedogni R., Gómez-Ros J. M., Scherillo A., Costa M. and Pietropaolo A., *EPL*, **127** (2019) 12002.
[9] Pietropaolo A., Angelone M., Bedogni R., Colonna N., Hurd, A. J., Khaplanov A., Murtas F., Pillon M., Piscitelli F., Schooneveld E. M. and Zitelhack K., *Phys. Rep.*, **875** (2020) 1.
[10] Monti V., Lega A., Altieri S., Costa M. and Bedogni R., submitted to *Nucl. Instrum. Methods A*.
[11] Werner C. J., *MCNP Users' Manual - Code Version 6.2.*, Report LA-UR-17-29981 (2017).
[12] Pola A., Bedogni R., Domingo C., Bortot D., Gómez-Ros J. M., Introini M. V., Martínez-Rovira I., Romero-Expósito M. and Costa M., *Nucl. Instrum. Methods A*, **927** (2019) 371.
[13] Bedogni R., Sperduti A., Pietropaolo A., Pillon M., Pola A. and Gómez-Ros J.-M., *Nucl. Instrum. Methods A*, **843** (2017) 18.
[14] Brown D. A. *et al.*, *Nucl. Data Sheets*, **148** (2018) 1.
[15] ISO, International Standardization Organization, *Reference Neutron Radiations - Part 2: Calibration Fundamentals of Radiation Protection Devices Related to the Basic Quantities Characterizing the Radiation Field*, ISO 8529-2 (2000).
[16] Bedogni R., Domingo C., Esposito A. and Fernandez F., *Nucl. Instrum. Methods A*, **580** (2007) 1301.
[17] Amgarou K., Bedogni R., Domingo C., Esposito A., Gentile A., Carinci G. and Russo S., *Nucl. Instrum. Methods A*, **654** (2011) 399.
[18] Kiyanagi Y., *Ther. Radiol. Oncol.*, **2** (2018) 55.
[19] Treccani M., Bedogni R., Pola A., Costa M., Monti V., Sans Planell O., Romano M., Durisi E., Visca L., Bortot D., Gomez-Ros J.-M., Ferrero M., Anglesio S., Giannini G. and Alikaniotis K., *Radiat. Prot. Dosim.*, **180** (2018) 304.